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INTRODUCTION

Gas pulsation and resultant vibration have long been synonymous with the compressing and transporting of gases under pressure. Not only has the speed of the present day reciprocating compressor shown a general upward trend over the past few years, but there has been a corresponding increase of horsepower/unit weight. The higher speeds, less mass resistance and increased efficiency have served to meet the ever changing needs of industry. Yet, in the wake of the many major component improvements and increased overall efficiency of the present day reciprocating compressor, new problem areas have developed and certain facets of essentially other known problem areas have taken on new proportions. Foremost in this category is excessive gas pulsation and the many undesirable effects connected in some manner with the pulsation phenomena which appear as a result of the reciprocating action of the compressor and the reaction of the supporting piping.

All air compressors require piping to either bring inlet air to the machine or to carry the compressed air away to the point of use. Some compressors require both. The air flow produced on both the inlet and discharge of a reciprocating air compressor is rapidly pulsating due to the characteristic design of the unit. This pulsating flow normally has a distinct natural frequency and wave length which must be considered in the support piping design to assure that a resonant condition, which ultimately may cause a variety of severe problems, will not exist between the natural frequency of the pulse and of the piping system. The adverse effect of pulsation upon the system is not always readily comprehended or fully realized due to the complexity of the pressure wave fluctuations produced within the cylinder air passages and the supporting piping. This paper will point out some of the important considerations concerning air pulsations when designing an air piping system.

PULSATIONS AND RESONANCE

As mentioned above, pulsating air flow is the very nature of reciprocating air compressors. Most piping and cylinder combinations simulate a system essentially equivalent to a pipe open at one end or an organ pipe. This by itself would cause little problem, but since we are talking about a finite pulse wave with a distinct frequency and amplitude combined with a variety of pipe lengths, the system exposes itself to resonance.

Resonance is the primary enemy of a good piping system. In an air piping system, resonance, defined as systematic sympathetic vibration of the air column in the pipe, can cause two major problems (1) severe pipe vibration resulting in ultimate premature component failures, and (2) supercharging. Included in the problems associated can be increased horsepower, increased noise levels and compressor valve breakage.

It has been tested and proven that resonance points can be predetermined for a given single pipe system. Compressor manufacturers recommend proper pipe sizes and various critical lengths of pipe to avoid. These recommendations are based on calculations which are a function of compressor configuration, speed, temperature, cylinder volume, pipe size and equivalent volume. The pulsating flow of air creates a traveling pressure wave which can be responsible for the existence of abnormal pressures in compressor piping. This results from the formation of standing pressure waves in the piping which are created by reflection when the length of the piping is such that its resonant frequency corresponds to the natural frequency of the traveling pressure wave. Peak resonance can occur at 1/4, 1/2, 3/4 and full wave length in the compressor cylinder and piping system. For double acting cylinders, 1/4 and 3/4 wave lengths pose the greatest problems since this is when the maximum reflection occurs at the open end of the system. However, resonance can also occur at various other harmonies (such as 1-1/4, 1-3/4, etc.).

Therefore, the first step in evaluating a given compressor and piping system is to determine the full load wave length for existing conditions. For a double acting cylinder this is

$$\lambda = \frac{60a}{2n}$$

where λ = wave length-feet
a = velocity of sound-feet/second
n = RPM

and twice this value for a single acting cylinder or a double acting cylinder with one end unloaded. The equivalent pipe length of the cylinder air passage and cylinder end is then determined by the expression

$$L = \frac{\lambda}{360} \times \tan^{-1}\left(\frac{2\pi V}{S\lambda}\right)$$

where L = equivalent pipe length-feet
V = equivalent cylinder and passage volume-cubic feet
S = area of inside of intake pipe-square feet

This value is then subtracted from the wave lengths to be avoided ($1/4\,\lambda$, $3/4\,\lambda$) and the values then determined are the actual lengths of pipe from the cylinder flange to the filter inlet flange at which peak resonance will occur.

As is true with any resonance point, there is a region extending approximately 25% on either side of each critical point where there will be some amplification. Therefore, on any given installation, there is a series of critical lengths to avoid rather than just points. The amplification at the two extremes of each critical length will be slight so some judgement can be used in the application of calculated lengths or published tables if it poses problems to strictly adhere to them. Simply avoiding these critical lengths on single pipe systems can almost always guarantee a satisfactory installation from the standpoint of resonance.

SINGLE PIPE OR COMPRESSOR SYSTEMS

The simplest case to evaluate and avoid problems is the one where a single pipe supplies air from a filter to a compressor cylinder and from the cylinder to a receiver. However, in those cases where it is impossible to stay out of a critical resonant range or where added inlet filter-silencer volume or aftercooler volume places the system closer to a resonant peak or the economics of changing the pipe length are prohibitive, two methods can be employed to correct the problem (1) installation of an orifice, or (2) installation of a volume bottle or pulsation dampener.

In a single pipe system, placing an orifice at the open end of the system can often eliminate a resonance problem and it is the most economic solution. On an inlet pipe, this would be where the filter is flanged to the piping and on the discharge pipe at the receiver inlet flange. In this type of system, there are pressure and displacement node points at various locations in the pipe. One of these node points occurs at the open end of the pipe. Placing an orifice here restricts the pulsating flow and detunes the system sufficiently to reduce the resonant amplitude of the pulsations so they are no longer objectionable. The orifice should be a thin plate, (approximately 1/8 - 3/16 inch thick) sharp edged machined opening approximately 1/2 the pipe diameter or 1/4 the cylinder diameter, whichever is smaller. Being a thin plate orifice, its effect on capacity is negligible; and pressure drop due to the size opening is small. It is possible, however, that other circumstances such as high filter maintenance or noise, or a combination of these and pipe vibration and supercharging will dictate a smaller orifice than normally needed for pipe vibration or supercharging only, which could result in noticeable capacity loss. In this case, it may be desirable to alter the piping length or install a pulsation bottle or dampener.

Volume bottles or pulsation dampeners are used to diminish the amplitude of the air pulsation before it has a chance to have any detrimental effect on the system piping. Because of this, they must be located as close to the compressor cylinder as possible, preferably flanged directly to the cylinder or frame connection. The inlet bottle limits any back pressure wave going from the cylinder upstream into the inlet pipe. The discharge bottle not only limits any back pressure wave from returning to the cylinder (which could cause valve problems), but also limits the wave going downstream into the discharge piping.

A pulsation bottle is a pressure vessel with no internal baffles that is sized as a function of the compressor cylinder characteristics and is relatively inexpensive. Compressor manufacturers should be able to advise the size bottle recommended for their various compressors.

A pulsation dampener is a commercial, internally baffled device that will serve the same purpose and is located at the same point as a pulsation bottle but reduces the pulse to lower levels than a pulsation bottle. Due to their construction, they are normally more expensive than pulsation bottles. These devices are manufactured by specialists who can guarantee that the residual pulse in the dampened air stream will not exceed an overall 2% of the absolute pressure in this stream.

MULTIPLE COMPRESSOR SYSTEMS

As discussed, single pipe systems can be relatively easily evaluated. Although the same principles apply, when two or more compressors are connected together, the system becomes much more difficult to evaluate. This is caused primarily because of the infinite possible phase relationship between the pressure waves of each compressor. These complex systems are best evaluated through the use of an analog study which is an electrical representation of the system evaluated under different variables on an analog computer. This type of analysis is quite expensive, but in many extremely complicated systems it is a good investment. Use of the analog study is a comprehensive subject all its own and is beyond the intent of this paper.

However, in many cases of installation of standard air compressors, an analog study is economically unfeasible, particularly when adding a compressor to an existing system. In those cases, there are certain basic fundamentals which can be applied to greatly diminish the possibility of problems occurring.

The use of manifolds or pipe headers is quite common since they decrease the amount of pipe required and are economically attractive. However, due to additional branches of piping, the probability of resonance and consequently supercharging increases. Supercharging is a phenomenon that occurs in a tuned inlet system operating at or near resonance. At the end of the suction stroke, a pressure wave in the pipe is near or at its peak at the inlet valves causing an elevated inlet pressure. This pressure holds the valves open longer than they should be and results in the valves being slammed to their seats at the beginning of the compression stroke. This slamming will break valves and increase overall noise level. Due to this elevated inlet pressure, the compressor acts as a booster compressor requiring additional horsepower. Tests have been performed to see if it was possible to satisfactorily operate an air compressor under supercharging conditions to increase capacity. It is possible with certain conditions, but the many ill effects created more than outweigh the slight advantage of increased capacity. Supercharging is definitely undesirable in compressed air piping.

If a header is used, it should have at least three times the cross-sectional area of the total area of the individual pipes leading from it to the compressors. Also, the piping between the header and the compressor should be the manufacturers recommended size and should avoid the critical ranges suggested. With a large header essentially an open end system is created, and the same rules that govern individual installations can normally be applied here. It may also be desirable to install flanges where this piping meets the header in case an orifice is needed later.

If individual piping is not used and a header system is not feasible, a pulsation bottle or dampener should be installed at each compressor to eliminate the possibility of pulsation problems.

GENERAL COMMENTS

In addition to the discussion on resonance, there are some general details which should be considered in the overall evaluation and design of a piping system. These are piping materials and cleanliness, piping configuration and mounting, the use of flexible connections, the use of temporary line filters, and the understanding of a freak phenomenon known as air hammer.

The materials for intake piping can be anything from some of the newer plastic pipes to standard schedule 40 pipe. The pipe must be strong enough to resist flexing or vibrating as the pulsating air flows through. Regardless of what is used, it is extremely important that the piping be cleaned and treated or painted if the selection of materials warrants it. The importance of pipe cleanliness and proper preparation cannot be over-emphasized since this piping may determine the success or failure of a new compressor. Similarly, the importance of a good compressor air intake filter cannot be over-emphasized. Discharge piping should conform to the applicable standards for the particular service conditions.

In arranging a piping layout, it is important that the air piping be as direct as possible with a minimum number of turns. If elbows have to be used, they should be the long radius type. Chill rings should be used for butt welds on intake piping to minimize the chance of weld beads and slag getting into the pipe and ultimately into the compressor at startup or later during operation. If piping runs are expected to be extremely long, it is recommended the pipe diameter be increased to minimize pressure drop. The piping should be rigidly anchored and supported, particularly in areas where changes in direction occur, so that no strain is placed on the compressor flanges or the piping itself. Supports should be spaced so that no part of the piping system has its natural frequency of vibration equal or nearly equal to the exciting frequency of the pressure wave. Spring piping supports can provide effective vibration control in one direction when properly applied. Hanging supports on long rods by themselves are not sufficient since the pipe is free to move in all directions. Provisions should also be made on discharge lines for expansion. This can be done by proper positioning of the supports and the use of bends or expansion loops.

Flexible connections are not normally required and are not recommended unless the type of compressor mounting allows a high degree of movement. If a compressor is essentially rigid, it is usually not the cause of pipe vibration. If a pipe is shaking, it is important to find out why and redesign the system rather than try to eliminate or prevent transmission of the vibration by installing a flexible connection.

Temporary line filters are sometimes used to aid in trapping any foreign debris that may have accumulated in the inlet piping. These are normally placed as close to the compressor inlet flange as possible and are only left in service for the first few hours of operation. The compressor manufacturers normally publish recommendations on the use and design of these filters.

Air hammer is a phenomenon which may occur in a discharge line in the area of an aftercooler or receiver or where there is a long run of pipe between the compressor and aftercooler and is characterized by a loud ringing sound that essentially sounds like someone hammering on the vessel or piping. It is a freak condition of resonance which normally can be eliminated only by changing the design configuration or the volume of the system. Usually the simplest solution is to install a pulsation bottle or dampener.

Evaluation of reciprocating compressor air piping is a vibratory problem involved with many variables. Some of these are precise. Some are constantly changing. Some are relatively unknown. All influence the final solution which often cannot be determined by exact laws of science. Occasionally, problems do develop in a system that appears satisfactory on paper. In such cases, the ultimate cure is a combination of science, experience and experimenting. However, taking into consideration the items discussed in this article greatly insures at the design level the elimination of problems occurring in the field.